

Central-edge asymmetry as a probe of Higgs-top couplings in $t\bar{t}h$ production at LHC

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The Higgs-top coupling plays a central role in the hierarchy problem and the vacuum stability of the Standard Model (SM). We study the CP violating Higgs-top couplings in dileptonic channel of $t\bar{t}h(\rightarrow b\bar{b})$ production at the LHC. We find that the CP violating interactions can affect the distribution of the rapidity difference of two leptons from the top decays ($\Delta y_{\ell+\ell^-}$) as a result of the presence of the top quark charge asymmetric term. Such an observable is frame-independent and has a good discrimination power of the CP violating couplings even in boosted regime. Then, we define a central-edge asymmetry A_{CE} to numerically distinguish the CP violating Higgs-top couplings, which can reach -40.3%, -26.6% and -9.5% for CP phase $\xi = 0, \pi/4, \pi/2$, respectively. Besides, we perform the binned- χ^2 analysis of $\Delta y_{\ell+\ell^-}$ distribution and find that the scalar and pseudo-scalar interactions can be distinguished at 95% C.L. level at 14 TeV HL-LHC.

I. INTRODUCTION

After the discovery of the Higgs boson at the LHC [1, 2], precision study of its properties becomes one of the most important tasks in theory and experiment. So far, the measured Higgs gauge couplings are compatible with the SM predictions at 1-2 σ level. However, the Higgs fermion couplings remain obscure. Among them, the Higgs-top coupling is of particular interest [3].

In the SM, the top quark has the strongest coupling with the Higgs boson. As such, the Higgs-top coupling plays an special role in the hierarchy problem [4] and the vacuum stability of the SM [5, 6]. Many models for physics beyond the SM related with these two problems predict a modified Higgs-top coupling. So, the precise measurements of Higgs-top coupling could give an insight on the pattern of fermion mass generation and the energy scale of new physics above the electroweak scale.

The most general Lagrangian of the $t\bar{t}h$ interaction can be parameterised as follows:

$$\mathcal{L} \supset -\frac{m_t}{v}\bar{t}(\cos\xi + i\gamma_5 \sin\xi)th, \quad (1)$$

where m_t is the top quark mass and v is the vacuum expectation value of the Higgs field. In the SM, $\cos\xi = 1$ and $\sin\xi = 0$ at leading order [7]. At the LHC, the Higgs-top coupling can be probed through the gluon fusion production ($gg \rightarrow h$) [8] and the associated production of the top pair with Higgs boson ($t\bar{t}h$) [9]. The former has a sizable cross section. However, it is not only altered by a modified Higgs-top coupling but also by new possible

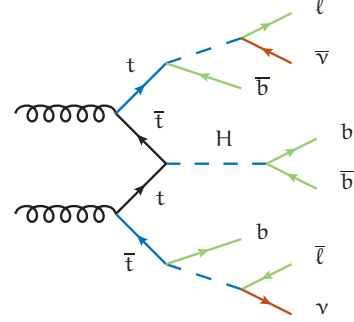


FIG. 1. Representative Feynman diagram of dileptonic channel of $t\bar{t}H$ production with $H \rightarrow b\bar{b}$ at the LHC.

colored particles, e.g. scalar tops or composite top partners. The latter is directly determined by the Higgs-top coupling, and thus is golden mode for this measurement [10–22]. The high order QCD and EW corrections to the $t\bar{t}h$ production have recently been studied [23–28]. With the data set of the 7 and 8 TeV runs of the LHC, the signal strengths in the $t\bar{t}h$ production channel have been measured by both ATLAS [29, 30] and CMS [31] in various Higgs decay modes: $b\bar{b}$, $\tau^+\tau^-$ and W^+W^- . Given the large boosted cross section of $t\bar{t}h$ [32], the LHC Run-2 would be able to pin down $t\bar{t}h$ production very soon.

In order to enhance the observability of $t\bar{t}h$ production, the dedicated reconstruction approaches of the top quark and Higgs boson have been proposed [33–35]. On the other hand, it is obvious that the measurement of the signal strength of $t\bar{t}h$ production alone is not sufficient to unveil the nature of the Higgs-top coupling in Eq. 1. Therefore, it is essential to investigate the kinematical distributions of $t\bar{t}h$ production at the LHC. In previous studies, the spin polarization/correlation effects of top quarks were used to probe the Higgs-top interac-

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tions in $t\bar{t}h$ production at the LHC. However, the sensitivity of the spin observables usually depends on the specific reference frames, the reconstruction efficiency of the top quark momenta and the kinematical cuts [36–40].

In this work, we propose to use the difference of rapidity of two leptons ($\Delta y_{\ell+\ell-}$) from the top decays to diagnose the CP property of Higgs-top couplings through the dileptonic channel of $t\bar{t}h(\rightarrow b\bar{b})$ production at the LHC. Such an observable is boosted invariant and can be distorted by the CP violating $t\bar{t}h$ interaction because of the appearance of top quark charge asymmetric term.

II. CALCULATIONS AND RESULTS

At the LHC, the dominant production of $t\bar{t}h$ is through the gluon fusion (c.f. Fig. 1). The presence of the CP violating Higgs-top interaction in Eq. 1 will lead to the top quark charge asymmetry term in $t\bar{t}h$ production. To see this, we take the s -channel gluon fusion subprocess as example. Assuming incoming gluons momenta q_1 and q_2 , outgoing top and antitop momenta p_t , $p_{\bar{t}}$, and Higgs momentum p_h , the amplitude is given by

$$\begin{aligned} \mathcal{M} = & \mathcal{M}_1 + \mathcal{M}_2 \\ & \propto \frac{\bar{u}(t)\Gamma_{t\bar{t}h}[(\not{p}_t + \not{p}_h) + m_t]\gamma_\rho v(\bar{t})}{(2q_1 \cdot q_2)(m_h^2 + 2p_t \cdot p_h)} J_{\mu\nu}^\rho \epsilon_1^\mu \epsilon_2^\nu, \\ & - \frac{\bar{u}(t)\gamma_\rho[(\not{p}_{\bar{t}} + \not{p}_h) - m_{\bar{t}}]\Gamma_{t\bar{t}h}v(\bar{t})}{(2q_1 \cdot q_2)(m_h^2 + 2p_{\bar{t}} \cdot p_h)} J_{\mu\nu}^\rho \epsilon_1^\mu \epsilon_2^\nu \end{aligned} \quad (2)$$

where $J_{\mu\nu}^\rho$ denotes the triple gluon interaction and $\Gamma_{t\bar{t}h} = (\cos\theta + i\gamma_5 \sin\theta)$. Its contribution to the cross section of $t\bar{t}h$ production involves the factor $Tr(\not{p}_t \gamma_\sigma \not{p}_{\bar{t}} \gamma_\tau \gamma_5)$, which is asymmetric in the interchange of t and \bar{t} and will affect the kinematics of the decay products of the top/anti-top quark.

In Fig. 2, we show the parton level correlations between $\Delta y_{\ell+\ell-}$ and $\Delta y_{t\bar{t}}$ in dileptonic $t\bar{t}h(\rightarrow b\bar{b})$ production for $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC. We can see that $\Delta y_{\ell+\ell-}$ indeed has a strong correlation with $\Delta y_{t\bar{t}}$, which indicates that the dynamical reason for changing Δy distribution comes from the above top quark charge asymmetric term rather than spin-correlation. For $\xi = \pi/4$ and $\pi/2$, the distributions of Δy spreads towards the large values, as a comparison with $\xi = 0$.

In Fig. 3, we present the parton-level distributions of $\Delta y_{\ell+\ell-}$ for $\xi = 0, \pi/4, \pi/2$ in Eq. 1 with $p_T^h > 40$ and 150 GeV at 14 TeV LHC. We can see that the SM interaction ($\xi = 0$) has more events than the mixed ($\xi = \pi/4$) interaction in the range of $|\Delta y_{\ell+\ell-}| < 1.5$, followed by pseudo-scalar interaction ($\xi = \pi/2$). While the distribution is reverse in the range of $|\Delta y_{\ell+\ell-}| > 1.5$. Such a behavior will give a small (large) asymmetry A_{CE} for $\xi = \pi/2$ ($\xi = 0$). Besides, it can be seen that the difference among $\xi = 0, \pi/4, \pi/2$ in $\Delta y_{\ell+\ell-}$ distribution is not sensitive to the increase of p_T^h . This indicates that the

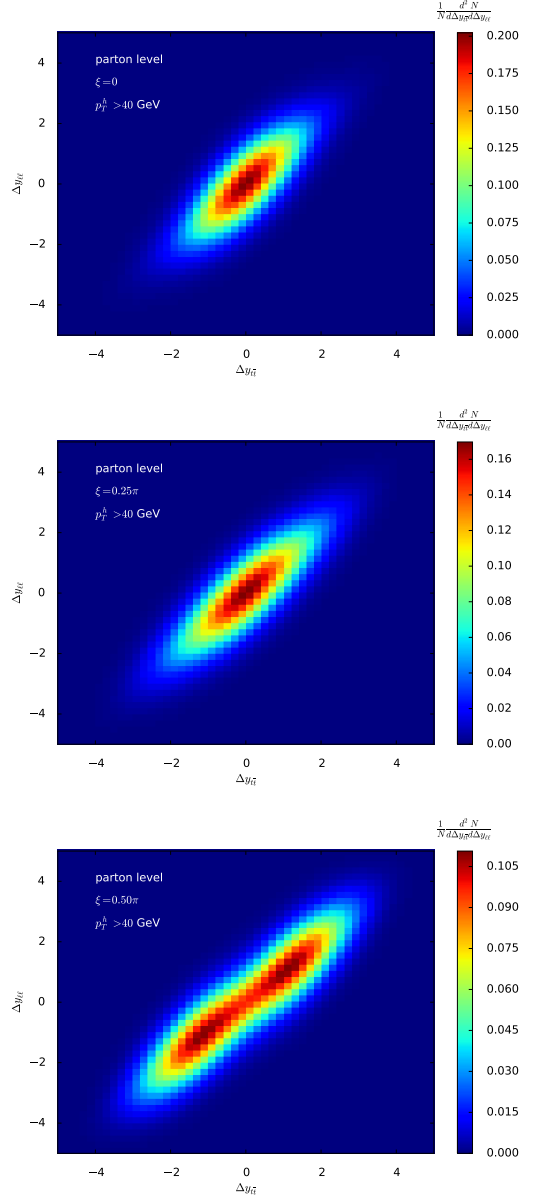


FIG. 2. Parton level correlation between $\Delta y_{\ell+\ell-}$ and $\Delta y_{t\bar{t}}$ in dileptonic $t\bar{t}h(\rightarrow b\bar{b})$ production for $\xi = 0$ (upper), $\pi/4$ (middle), $\pi/2$ (lower) at 14 TeV LHC.

variable $\Delta y_{\ell+\ell-}$ has a good discriminating power for the different CP phases even in boosted phase space.

To quantitatively describe the difference in Δy distributions for different CP phase, we define a central-edge asymmetry,

$$A_{CE} \equiv \frac{\sigma_{|\Delta y_{\ell+\ell-}| > |\Delta y_{\ell+\ell-}^0|} - \sigma_{|\Delta y_{\ell+\ell-}| < |\Delta y_{\ell+\ell-}^0|}}{\sigma_{|\Delta y_{\ell+\ell-}| > |\Delta y_{\ell+\ell-}^0|} + \sigma_{|\Delta y_{\ell+\ell-}| < |\Delta y_{\ell+\ell-}^0|}}, \quad (3)$$

where Δy^0 is the critical value of $\Delta y_{\ell+\ell-}$ that is determined from the crossing point of $\Delta y_{\ell+\ell-}$ distributions for the different CP phase. The prediction of A_{CE} significantly different from the SM value of $t\bar{t}h$ production

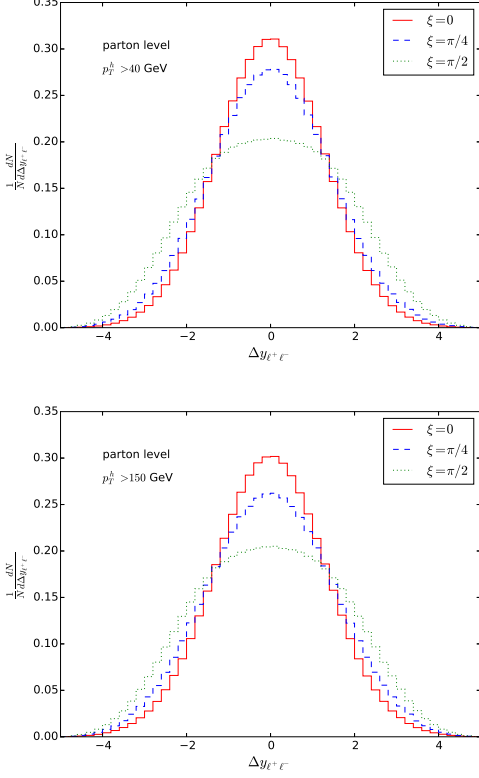


FIG. 3. Normalized parton-level $\Delta y_{\ell^+\ell^-}$ distribution in $t(\rightarrow b\ell^+\nu_\ell)\bar{t}(\rightarrow \bar{b}\ell^-\nu_{\bar{\ell}})h$ production with $p_T^h > 40$ GeV (upper panel) and $p_T^h > 150$ GeV (lower panel) at 14 TeV LHC.

would strongly indicate the the non-standard CP violating Higgs-top interaction in Eq. 1.

ξ	$\mathcal{A}_c(\ell^+\ell^-)(\%)$	
	$p_T^h > 40$ GeV	$p_T^h > 150$ GeV
0	-52.00	-48.92
$\pi/4$	-41.13	-35.58
$\pi/2$	-16.53	-16.73

TABLE I. Parton-level values of $\mathcal{A}_c(\ell^+\ell^-)$ with $p_T^h > 40, 150$ GeV for $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC.

In Table I, we numerically give the parton-level values of $\mathcal{A}_{CE}(\ell^+\ell^-)$ for $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC. For $p_T^h > 40$ (150) GeV, we can see that the value of $\mathcal{A}_{CE}(\ell^+\ell^-)$ predicted by the SM is about -52%(-49%), while it becomes about -41%(-36%) and -17%(-17%) for the mixed and pseudo-interactions, respectively.

In the following, we study the observability of the dileptonic channel of $t\bar{t}h$ production with the sequent decay $h \rightarrow b\bar{b}$ and the charge asymmetry $\mathcal{A}_{CE}(\ell^+\ell^-)$ for CP phases $\xi = 0, \pi/4, \pi/2$ by including the detector effects at 14 TeV LHC. The dominant SM backgrounds are the $t\bar{t}b\bar{b}$ and $t\bar{t}Z(\rightarrow b\bar{b})$ productions. Since the signal and backgrounds have good discrimination in the high p_T^h regime,

we apply the jet substructure technique to reconstructing the Higgs boson.

We use MadGraph5_aMC@NLO [41] to generate the parton-level signal and background events, in which the top quark and Higgs boson are further decayed with Madspin [42]. The signal $t\bar{t}h$ and background $t\bar{t}Z$ is matched up to 1 jets by using MLM matching scheme [43] with $xqcut = 30$ GeV. We take $qcut$ to $\max(xqcut + 5, xqcut * 1.2)$ [44] in our simulation. The CTEQ6M parton distribution functions (PDF) [45] are chosen for our calculation. We set the renormalisation scale μ_R and factorisation scale μ_F to be $\mu_R = \mu_F = (m_h + 2 * m_t)/2$. We use PYTHIA6 [46] for implementing parton showering and hadronization. Delphes3 [47] with input of default ATLAS detector card is used for simulating detector effects. In this simulation, we take the b -jet tagging efficiency as 70% with the other light quark and gluon mis-tagging probability 1% [48].

Events which contain exactly two opposite sign leptons and at least four jets will be selected in our following analysis. These two leptons should have $p_T > 15$ GeV, $|\eta| < 2.5$ and be isolated. Particle-flow objects in Delphes3 output other than isolated leptons are then used for jet clustering with Fastjet [49]. We adopt the BDRS method for tagging Higgs jet substructure: (1) reconstructing the fat jets using C/A algorithm [50] with radius $R = 1.5$ and $p_T^h > 150$ GeV; (2) breaking each fat jet by undoing the clustering procedure. Higgs jet candidate is taken as the leading fat jet that has large mass drop $\mu < 0.67$ and not too asymmetric mass splitting $y > 0.09$ at certain step during the de-clustering; (3) filtering the Higgs neighbourhood by re-running the C/A algorithm with a finer angle $R_{filt} = \min(0.3, R_{j_1, j_2}/2)$ and taking the three hardest subjects; (4) applying b -tag on the two leading subjects. The Higgs jet candidate is required to have both subjects being b -tagged. The pileup effects on the Higgs mass can be controlled by the BDRS filtering. For event that contains the Higgs jet candidate, we proceed further to reconstruct narrow jets. The constituents of the Higgs jet candidate are removed from those particle-flow objects. The remnants are clustered with the anti- k_T jet clustering algorithm [51] with the cone radius of $R = 0.4$ and are required to give at least two narrow jets, in which exactly two are b -tagged.

In Table II, the cut-flow of cross sections of the signal and background events is presented for 14 TeV LHC. The cross sections of $t\bar{t}h$ are normalized to their NLO QCD values [26]. After the cut $p_T^{BDRS}(b\bar{b}) > 150$ GeV, the $t\bar{t}b\bar{b}$ background is reduced by almost $\mathcal{O}(10^{-2})$, while the signals only by $\mathcal{O}(10^{-1})$. The Higgs mass window cut $|m_{b\bar{b}}^{BDRS} - 125| < 10$ GeV will further suppress $t\bar{t}b\bar{b}$ and $t\bar{t}Z$ backgrounds by one order. After all cuts, the significance S/\sqrt{B} of $\xi = 0, \pi/4, \pi/2$ can reach 5σ when the luminosity $\mathcal{L} = 795, 993, 1276 \text{ fb}^{-1}$. The typical values of S/B are about 30%.

In Table III, we present the values of $\mathcal{A}_{CE}(\ell^+\ell^-)$ at the reconstructed level after all above cuts. It can be seen that the values of $\mathcal{A}_{CE}(\ell^+\ell^-)$ are mildly diminished

cut	$t\bar{t}h(\xi=0)$	$t\bar{t}h(\xi=\pi/4)$	$t\bar{t}h(\xi=\pi/2)$	$t\bar{t}b\bar{b}$	$t\bar{t}Z(\rightarrow b\bar{b})$
$2\ell, p_T^\ell > 25 \text{ GeV}, \eta_\ell < 2.5$	13.31	9.14	5.31	2424.73	1.56
$p_T^{\text{BDRS}}(b\bar{b}) > 150 \text{ GeV}$	2.02	1.47	0.97	19.24	0.25
2 non-Higgs b 's	0.28	0.21	0.15	1.41	0.04
$p_T^b(\text{non-}h) > 30 \text{ GeV}, \eta_b(\text{non-}h) < 2.5$	0.22	0.17	0.13	1.13	0.03
$ m_{b\bar{b}}^{\text{BDRS}} - 125 < 10 \text{ GeV}$	0.053	0.048	0.042	0.09	0.0013

TABLE II. Cut flow of the cross sections of the signal $t\bar{t}h$ for $\xi = 0, \pi/4, \pi/2$ and backgrounds $t\bar{t}b\bar{b}$ and $t\bar{t}Z$ at 14 TeV LHC. The cross section is in unit fb.

ξ	N_{events}		$A_{CE}(\ell^+\ell^-)(\%)$
	$\Delta\eta > 1.5$	$\Delta\eta < 1.5$	
0	2653	6230	-40.26
$\pi/4$	4239	7312	-26.60
$\pi/2$	7774	9400	-9.47

TABLE III. Reconstructed level values of $A_{CE}(\ell^+\ell^-)$ at 14 TeV LHC.

by the event selections, but are still obviously different for $\xi = 0, \pi/4, \pi/2$.

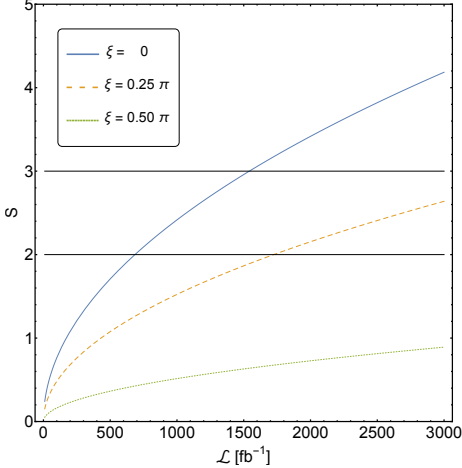


FIG. 4. The significance of A_{CE} in dileptonic $t\bar{t}H(\rightarrow b\bar{b})$ production versus the integrated luminosity \mathcal{L} for the CP phase $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC.

A straightforward Gaussian estimate of the significance of A_{CE} is given by

$$S = \frac{A_{CE}}{\delta A_{CE}} \simeq \frac{|\Delta\sigma_{\Delta y_{\ell+\ell^-}}| \mathcal{L}}{\sqrt{\sigma_{\text{tot}} \mathcal{L}}}. \quad (4)$$

In Fig. 4, we show the significance of A_{CE} versus the luminosity \mathcal{L} at 14 TeV LHC. We find that the SM prediction of A_{CE} can be observed at 3σ level when $\mathcal{L} = 1500 \text{ fb}^{-1}$, while for the mixed and pseudo-scalar interactions,

their significance is less than 3σ in the run of 14 TeV LHC.

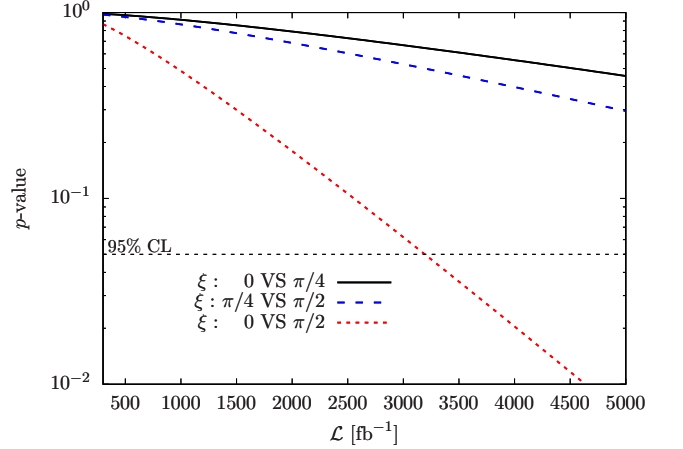


FIG. 5. The significance of $A_{CE}(\ell^+\ell^-)$ in dileptonic $t\bar{t}H(\rightarrow b\bar{b})$ production versus the integrated luminosity \mathcal{L} for the CP phase $\xi = 0, \pi/4, \pi/2$ at 14 TeV LHC.

Finally, we estimate the CP discrimination in Higgs-top couplings by calculating the binned- χ^2 of the $\Delta y_{\ell+\ell^-}$ histogram at reconstructed level. In Fig. 5, we can see that the 14 TeV LHC will be able to distinguish $\xi = 0$ and $\xi = \pi/2$ interactions at 95% C.L. level if the luminosity $\mathcal{L} \simeq 3200 \text{ fb}^{-1}$.

III. CONCLUSIONS

In this work, we investigate the CP violating Higgs-top couplings in dileptonic channel of $t\bar{t}h(\rightarrow b\bar{b})$ production at the LHC. We find that the CP violating interaction can distort the distribution of the rapidity difference of two leptons from the top decays because of the presence of the top quark charge asymmetric term. We also find that such an observable has a good discrimination power of the CP violating couplings in boosted regime. To numerically show the difference in $\Delta y_{\ell+\ell^-}$ distributions, we define a central-edge asymmetry A_{CE} , which can reach -40.3%, -26.6% and -9.5% for CP phase $\xi = 0, \pi/4, \pi/2$, respectively. Besides, we simply perform the binned- χ^2 analysis of $\Delta y_{\ell+\ell^-}$ distribution and find

that the scalar interaction and the pseudo-interaction can be distinguished at 95% level at 14 TeV LHC with $\mathcal{L} \simeq 3200 \text{ fb}^{-1}$ of integrated luminosity.

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